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THE EFFECT OF FLY ASH ON THE WORKABILITY AND MECHANICAL PROPERTIES OF CONCRETE SLABS: A REVIEW

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ABSTRACT

Cement production in the world accounts for 5% of the annual anthropogenic global carbon dioxide production. This is mainly due to the vast amount of cement is used in the making of concrete slabs. However, the process of production of cement is not environmentally friendly. There is a need for other substitutes or partial replacement of cement in concrete slabs. Fly ash is one such material. Fly ash is a by-product of coal combustion in thermal power stations. Out of hundreds of millions of metric tons of fly ash are produced worldwide only 20–40% is used for productive purposes. The rest is sent to the landfills to be dumped contributing to the pollution of environment. The use of fly ash as a partial replacement of cement in concrete has economic, environmental and mechanical advantages. There are number of studies on the effect of fly ash on different types of concrete. However, only a limited number of studies showing effect of varying fly ash volume fraction on the workability in concrete paste and strength properties in concrete slabs. Therefore, this paper reviews the effect of partial replacement of cement with fly ash on the workability of concrete and the resultant mechanical properties of the concrete slabs.

***KEYWORDS:** Fly Ash, Concrete, Workability, Compressive Strength & Flexural Strength*

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Original Article

1. INTRODUCTION

Concrete material is a very important construction material. Its popularity stems from the fact that the raw materials used in concrete are readily available all around the world. The mixing of concrete however is a specialised science which requires a lot of attention. Concrete exists in two states namely, plastic and hardened state. In the plastic state concrete is in a paste form and mouldable whereas in the hardened state concrete is in rigid form. The mechanical properties of the concrete depend on the properties of the raw materials and their mixing ratios. Concrete used in slabs and its basic form constitutes of Portland cement, aggregates, admixtures and water which is required for the hydration reaction. In fact, cement which is a key ingredient in the manufacture of concrete is a huge contributor to air pollution during its manufacture. In this perspective, there is a need for the development and research for other materials that can partially replace cement in the concrete mixture making the whole process more environmentally friendly [1]. Table 1 shows the basic ingredients necessary to make concrete for use in slabs in their respective proportions.

Concrete when first mixed is in a plastic state which allows it to be mouldable. It is then cured to a solid mass. The properties of the concrete in both plastic state and post cure hardened mass are affected by the physical and chemical composition of the constituent ingredients in the mixture. One of the key requirements of concrete is that is should possess good workability in its plastic state to allow ease of handling, placing, compacting and finishing. Furthermore, in its solid form it must be tough enough to carry load, be durable to weather elements, wear and chemical attack resistant [2].

Table 1: Basic Ingredients in the Making of Concrete for Slabs[3, 4]

Ingredient	Range (%)
Admixture	5–10
Entrained air	6–8
Cement	10–15
Coarse and fine aggregates	60–75
Water	15–21

The high cost of cement as the binder in concrete slabs has motivated research into alternatives. Moreover, the production of cement has a high emission of carbon dioxide (CO_2) which contributes to global warming. This has led to research the use of fly ash as a partial replacement of cement in concrete slabs. Fly ash is a by-product of burning pulverized coal in thermal power plants. Fly ash particles consist of inorganic materials which include large quantities of silica and alumina with some trace quantities of unburnt carbon [5]. Approximately, 900 million metric tonnes of fly ash is produced worldwide. However, only a small percentage of about 20–40% is being utilized for various value added products [6]. The unburned coal residue from the coal fired boilers is carried away from the burning zone with the flue gases and collected mechanically or by the use of electrostatic separators. The heavier material of the burned residue drops down the furnace. This heavier residue is referred to as bottom ash [7]. Bottom ash is not suitable for use in concrete slab mixtures. However, it can be used in the manufacture of masonry blocks. Fly ash consists of inorganic, incombustible matter present in the coal that has fused during combustion into a glassy, amorphous structure [8]. The physical and chemical properties of fly ash produced depend largely on the type of coal used, combustion equipment and type of fly ash collection system [9]. Though, percentage quantity of fly ash that gives the optimum strength properties in concrete slabs is not known. Besides, the resultant fly ash by-product if disposed of in dumps, tends to result in environmental pollution which includes contamination of the ground water, soil and creation of fugitive dust particles [10, 11, 12]. In this regard therefore, this study reviews the effect of fly ash as a partial replacement of cement on the workability and mechanical properties of concrete slabs.

2. PORTLAND CEMENT

Cement is defined as a fine powdery material containing silicates of calcium, formed out of raw materials consisting of calcium oxide, silica, aluminium oxide and iron oxide [13]. Modern life without cement is almost impossible to conceive as cement is the inorganic binder for concrete material for buildings and civil engineering constructions. Furthermore, the cement and concrete industry are very important sectors of the world economy and in every country. It is responsible for job creation and numerous benefits in secondary industries. In fact, concrete is second most used material in the world next to water. In terms of production, it surpasses its closest rival, which is steel by 30 times in volume and 10 times in mass [14]. Concrete material is used widely as it does not require sophisticated equipment to use, is easily mouldable and sets rapidly within a few hours [15]. However, cement production is energy intensive and environmentally unfriendly. Furthermore, it uses a lot of non-renewable natural resources in the process generating significant amount of CO_2. Statistics show that 5–6% of all CO_2 gases generated worldwide is from cement production alone [16].

There are over 10 different types of cements that are used in the construction industry, and they differ significantly in their composition and are manufactured for different end uses. Some of these types of cement types include; Ordinary Portland cement (OPC), Portland Pozzolana Cement (PPC), Rapid Hardening Cement, Quick Setting Cement, Low Heat Cement, Sulphates Resisting Cement, Blast Furnace Slag Cement, High Alumina Cement, White Cement, Coloured cement, Air Entrained Cement, Expansive Cement and Hydrographic Cement[17]. Generally, Ordinary

Portland cement is the most suited for use in concrete slabs. Hence, this study will from this point on focus solely on the use of Ordinary Portland Cement hence after referred to as just Portland cement.

Portland cement got its name from Joseph Aspdin in 1824 who named it after the cliffs on the isle of Portland in England [18]. The manufacturing process of Portland cement involves mining, crushing, grinding of limestone and clay, blending of raw materials and calcining the materials in a kiln. Thereafter, cooling the resulting clinker, mixing the clinker with gypsum and milling, storing and bagging the finished cement. The chemistry of cement production begins with the decomposition of clay minerals into Silicon dioxide (SiO_2) and Aluminium Oxide (Al_2O_3) on one hand and of calcium carbonate ($CaCO_3$) at about 900°C to give CO_2 on the other hand in a process known as calcination. Thereafter clinkering process is carried out in which the Calcium Oxide (CaO) reacts at approximately 1450°C with silica, alumina and ferrous oxide to form silicates, aluminates, and ferrites of calcium. The resultant clinker is then ground with gypsum and other additives to produce cement.

There is a serious environmental problem in the production of cement and one possible way to increase the sustainability and lessen pollution levels is to use alternative raw materials from those being used currently. One such method involves using fly ash which has been identified as a potential source of silica and alumina in the cement manufacturing process [19, 20]. The other option which is also viable is to use gypsum as a starting material to produce sulphuric acid and cement. There is however, another less researched method which has not been well researched and understood which may be economically viable, which is combining fly ash and gypsum as raw materials in the manufacture of cement [15]. The other available method is the partial substitution of Portland cement with fly ash during the manufacture of concrete slabs which is the main focus of this study.

3. FLY ASH

Fly ash is a pozzolanic material. Pozzolans are defined as siliceous material, which on their own have no cementitious properties. But whenever pozzolans are processed and in finely divided form they can react. The pozzolans react in the presence of water with lime to form compounds with low solubility having cementitious properties [21].

Disposal and management of fly ash is a problem in thermal power stations. Due to the fine particle size of fly ash it is able to penetrate to the pulmonary region of the human lungs where it accumulates and behaves like a cumulative poison [22]. Furthermore, the submicron fly ash particles when they enter the airway are deposited on the alveolar walls in the human lungs where heavy metals contained in fly ash which include Nickel (Ni), Cadmium (Cd), Antimony (Sb), Arsenic (As), Chromium(Cr) , Lead (Pb) can be transferred to the blood plasma through the cell membranes [22]. There has not been much research carried out on the effect of inhaling fly ash particles on different animal species. In this perspective, there is a need to come up with an environmentally friendly method of disposal of fly ash. Several methods have been developed which include the use of fly ash in bricks, agriculture, road construction, concrete and embankments [23].

Fly ash used for road construction saves top soil which is otherwise normally used. There by avoiding excavating of soil elsewhere for the use of top soil in road construction. Furthermore, fly ash increases the stability and durability of the road [24]. Use of fly ash in agriculture improves the permeability of soil, improves fertility status of the soil, improves water holding capacity, optimizes pH value and provides micro and macro nutrients such as Potassium (K), Phosphorus (P), Calcium (Ca), Magnesium (Mg), Zinc (Zn) and Manganese (Mn). However, there has not been much research carried

out on the effect of the heavy metals present in fly ash on the soil and ground water contamination when used for agricultural purposes [24, 22].

The use of supplementary cementitious material such as fly ash to reduce cement quantity in concrete mixtures has become a topic of great importance [25]. Significant quantities of cement is necessary to produce large quantities of concrete slabs, this tends to lead to a high pollution rate due to increased carbon emission during the manufacture of cement [26]. Furthermore, the cost per unit of concrete slabs can be reduced significantly by incorporating fly ash in concrete [27]. It is worth noting that cement is the most costly ingredient in the manufacture of concrete slabs.

Numerous successful research has been done into the incorporation of fly ash, silica fume and other types of inorganic waste and agricultural by-product materials in concrete slabs [28]. Use of fly ash in concrete mixture brings about numerous benefits such as economical, technical and environmental advantages through the conservation of natural resources and reduction of greenhouse gases emitted during the production of cement [29]. However, not much research has been carried out for the effect of fly ash has on the health of the workers in the concrete industry. Most research has focused on the advantages and disadvantages of its use in terms of concrete properties.

A study carried out by Kumar [30] concluded that the use of fly ash as a partial replacement of cement is gaining importance due to the improved long term durability of concrete coupled with the ecological benefits [30]. The use of supplementary cementing materials in concrete mixture helps to reduce the quantity of cement and improves the strength, workability and the durability of concrete [31, 32, 33]. As a result of research that has been carried out it has been shown that it is possible to replace up to 50% of Portland cement with fly ash. This reduces the cost and the permeability of concrete while increasing the strength and durability.

Use of fly ash as partial replacement of cement takes advantage of the pozzolanic property of fly ash. Portland cement mixed with pozzolanic material is referred to as pozzolanic cement. Pozzolanic cement has several advantages such as improved resistance to chemical attack, lower heat of hydration, economy, improved workability, reduction of bleeding and increased impermeability [21]. The properties of concrete containing fly ash are influenced by the physical, mineralogical and chemical properties of the fly ash used. The quality of fly ash varies widely with type of coal used [34]. It is therefore necessary to grade and classify the fly ash. ASTM C618 defines two main classes of fly ash which include Class F and Class Cfly ash. Table 2 shows the chemical composition of the two main classes of fly ash in comparison with the properties of Portland cement.

Class F fly ash is produced by burning of anthracite bituminous coal which is also called low calcium fly ash. As a result of its chemical composition, Class F fly ash has only pozzolanic properties.

Table 2: Classification of Fly Ash Based on its Chemical Properties [35]

Chemical Compound	Pozzolan Type		
	Class F	Class C	Portland Cement
SiO	54.90	39.90	22.60
Al_2O_3	25.80	16.70	4.30
Fe_2O_3	6.90	5.80	2.40
CaO	8.70	24.30	64.40
MgO	1.80	4.60	2.10
SO_3	0.60	3.30	2.30
Na_2O & K_2O	0.60	1.30	0.60

Whereas, Class C fly ash is produced by burning sub bituminous lignite. As a result of the availability of free lime, Class C has both pozzolanic properties and cementitious properties [36]. The pozzolanic reactivity of fly ash is influenced by a number of factors which include its fineness, glass content and acidic oxide content [37].

Fly ash varies widely in its properties to the extent that no two fly ash samples from different thermal power plants are exactly identical in their properties. Therefore, there is a need to characterize the fly ash prior to use and classify it accordingly. The replacement level of cement with fly ash varies according to its class. On one hand, Class F fly ash replacement can be done between 15 and 25% by mass.[38]. On the other hand, Class C fly ash replacement levels are higher and range from 15 to 40% by mass [37].

There is a relationship between the pozzolanic activity and size of the fly ash particles. The coarser the fly ash particles the lower the pozzolanic activity [39]. This is attributed to the fact that when the fineness of the fly ash increases the surface silanol groups also increase proportionally. This assists in further crystalline hydrate formation when the fly ash reacts with free lime from the hydration of cement. Fly ash tends to improve the workability of concrete due to its spherical shape as it gives what is commonly referred to as ball bearing effect. The ball bearing effect increases the flow ability of the concrete mixture [40]. On the other hand, irregular shaped fly ash particles tend to lead irregular compaction. This results in the formation of inter particle voids within the concrete mixture [41]. Concrete slabs made from finer fly ash particles of size ≤ 10 μm gives benefits such as reduction in the amount of water required in the concrete mixture and increasing the strength of the transition zone. Other benefits are lowering the bleeding during the preparation of the concrete mixture as well as increasing the compressive strength of the concrete slabs [41, 42, 43].

The use of fly ash in concrete slabs has gained popularity over the past years. This is because of an improvement in the durability, workability and ecological benefits of using fly ash in the mixture. Advancements in thermal power station processes have also improved the quality of fly ash obtained making it more suitable for use in cement composites [44]. Fly ash increases the durability of concrete by mitigating the alkali-silica reactions. Increasing resistance to sulphate attack and reduced ingress of chloride and water which cause corrosion of steel reinforcements [45]. It is worth noting that fly ash concrete with replacement levels of above 50% is also known as High Volume Fly Ash Concrete (HVFA) [46].

Portland cement used in concrete is rich in lime content (60–70%)whereas in contrast fly ash lime content is low (<7%)[47]. Fly ash contains mainly reactive silicates (28.87%) as shown in the study by Akbar [48], while Portland cement on the other hand contains smaller amounts. Free lime is generated when Portland cement reacts with water as shown in equation 1. The chemical properties of fly ash allow the pozzolanic activity of the fly ash to combine with the free lime from cement producing a cementations compound as shown in equation 2.

$$Portland\ Cement + Water\ \rightarrow Calcium\ silicate\ hydrate + Free\ Lime \quad (1)$$

$$Free\ Lime + Fly\ Ash + Water \rightarrow Calcium\ silicate\ hydrate \quad (2)$$

The pozzolanic reaction gives additional strength to the concrete. In addition, efflorescence is also prevented due to the mopping up of free lime in the reaction which is responsible for the efflorescence phenomenon [49].

4. Properties of Concrete Paste Containing Fly Ash

Addition of fly ash to the concrete paste affects the properties of the resultant concrete slab such as the workability, slump, bleeding rate, setting, heat of hydration and permeability of the concrete mixture. The effects of fly ash on these properties are discussed under the following six sub sections.

4.1 Concrete Workability

Concrete mixture workability is defined as the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity [50]. Workability in a broader context has an effect on the consistency, flowability, pumpability, compactibility and harshness of the concrete mixture [51, 52, 53]. Workability of concrete determines the ease of which concrete can be placed, compacted and moulded. The addition of fly ash into a concrete mixture has a beneficial effect on the rheological properties of concrete and increases its workability. Fly ash increases the paste volume leading to an increase of plasticity and cohesion [54]. Moreover, fly ash particles due to their spherical nature tend to act as a lubricant to the aggregates interface reducing friction and increasing workability of the concrete mixture. Generally, the higher the volume fraction of fly ash the better the workability of the concrete mixture [55]. Ismail [4] studied the fly ash particles from Malaysia thermal power station under a Scanning Electron Microscope (SEM). 1 shows scanning electron images obtained for the fly ash from Malaysia power plants and fly ash from South Africa thermal power stations. The SEM images show the fly ash has the typical spherical appearance from both countries. Hence, Ismail [4] concluded that the fly ash was composed of mostly small spherical particles ranging from 2 to 14μm in diameter [8].

The spherical shape of the fly ash particles as shown in Figure 1 improves the workability of concrete making it easier to handle, place and finish. This shape of the particles allows the concrete to flow smoothly and increases its workability significantly. Workability of concrete is also linked to the water content. Moreover, fly ash lowers the required amount of water in the manufacture of concrete. In fact, for each 10% volume fraction of fly ash added to concrete there is a water reduction of about 3% [7].

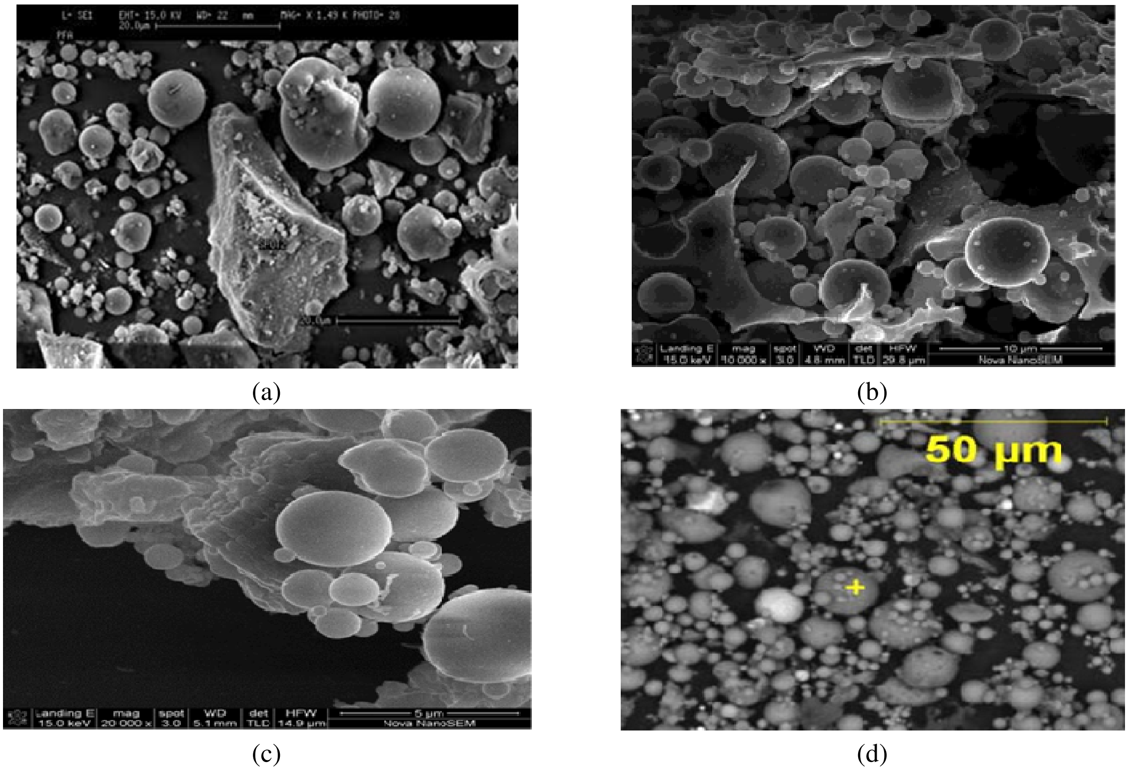

Figure 1: Showing the SEM for the Cenosphere Fly Ash Particles from Different Areas (a) Malaysia (b) Hendrina, South Africa (c) Matla, South Africa [8];[56] (d) Typical Fly Ash Particle [57].

However, Ramaswamy [58] concluded that the water reduction amount is dependent on the fineness of the fly ash particles. That is, the finer the fly ash particles the greater the reduction in water demand. The finer fly ash is preferred as it leads to a bigger saving in cost by reducing water demand. There is an increase of 21% in flow of concrete for 50% volume fraction of fly ash. This is considered by Ramswamy [59], the best replacement level of fly ash replacement in concrete to obtain the best workability.

4.2 Slump of Concrete

Slump is a relative measurement in concrete consistency and fluidity. It shows the flow and overall workability of freshly mixed concrete. The primary purpose of the slump test is to assess the consistency of fresh concrete. Indirectly, the slump test ensures that the water content of the concrete does not deviate significantly from the required design. Slump of concrete is related to the workability of concrete as it measures the water content in concrete. Concrete slump is in three general forms as shown in Figure 2. In collapsed slump the concrete collapses, in shear slump the top part of the concrete shears off sideways and in true slump the concrete sample keeps to shape. A collapsed slump is an indication of concrete containing too much water.

Ravina [61] study established that partial replacement of cement with fly ash reduces the slump of concrete [61]. The lower slump loss of concrete mixture containing fly ash can be attributed to the lower amount of water in the concrete containing fly ash. However, lower water quantity required might have an adverse effect on workability yet show a good slump value. The concrete paste might not flow as well due to the lower amount of water making it harder to mould with accuracy.

4.3 Bleeding of Concrete

Bleeding of concrete is the physical migration of water towards the top surface of concrete. Bleeding increases finishing times, produces laitance at the surface, decreases the mechanical strength, wear resistance and bond strength of concrete [62]. Water rising to the surface of concrete carries fine particles of cement which weaken the top portion and forms laitance. This lowers the resistance of concrete to abrasion. Bleeding water may accumulate under the coarse aggregate and reinforcement. These large voids under the particles may lead to weak zones and reduce the bond strength between the concrete paste and the aggregates. When water moves towards the top, the top portion tends to become porous and weak decreasing the resistance of concrete to adversely cold temperature alternating with warmer temperatures.

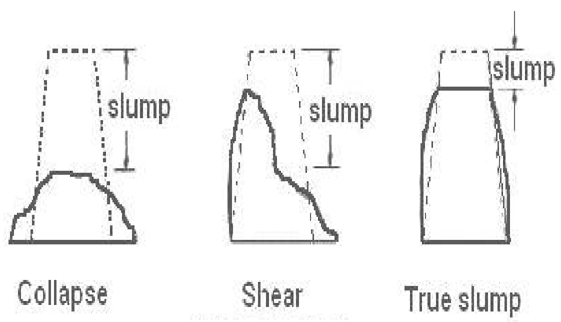

Figure 2: Three Types of Concrete Slump *[60]*.

Bleeding is however necessary as it helps to replace the water from the surface that has been lost by evaporation. This phenomenon prevents premature drying out of concrete which would result in cracks occurring. Plastic shrinkage cracking occurs if there is rapid drying on the concrete surface, whenever the rate of evaporation exceeds the rate of

concrete bleeding. Plastic cracks tend to occur within 3–5 hours while the concrete is still in its plastic state if it dries out prematurely [62]. Plastic settlement cracks occur if there is excessive bleeding and settlement from the concrete. Bleeding capacity is calculated using Equation 3.

$$Bleeding\ Capacity\ (\%) = \frac{QM}{10SV} * 100 \tag{3}$$

where, Q is the total bleed water (ml), M is the total batch mass of concrete (kg), S is the mass of concrete in the sample (kg) and V is the free mixing water in the concrete (l).

Ravindrarajah [45] study tested the bleeding of concrete mixture containing fly ash. The author concluded that the bleeding rate and bleeding capacity increases with increased fly ash replacement of cement for the first 120 minutes. After 120 minutes the bleeding rate stabilised and did not increase significantly with time. For the first 90 seconds there was a significant increase in the quantity of bleed water. Concrete containing 30% of fly ash volume fraction was reported to give the highest bleed quantity at 90 minutes over other fly ash volume fractions. In contrast, study by Yao et al [46] who reported a decrease in bleeding with increased fly ash replacement levels [63]. The discrepancies between the two authors can be attributed to the origin of the fly ash used.

4.4 Setting of Concrete

Setting of the concrete mixture is the onset of rigidity in the concrete mixture. The cement matrix is the principal ingredient in the setting of concrete. The setting time of concrete is associated with the workability of concrete. Moreover, setting time has an effect on the time available for transportation, placing and compaction of concrete [64]. The rate of setting of concrete influences how the concrete paste can be used and its shelf life. Addition of fly ash has an influence on the concrete setting rate. Fly ash tends to increase or decrease the setting time of concrete depending on its volume fraction within the mixture and the class of fly ash used [44]. With Class F (low lime) fly ash, the setting and hardening of concrete is delayed. Class C (high lime) fly ash, however, has either rapid or delayed setting time depending on the constituent properties of the fly ash [65]. Naik [49] carried out research on the influence of fly ash volume fraction on the setting and hardening of concrete. The study concluded that the addition of fly ash of volume fraction up to 60% caused significant delay in the setting of concrete. Generally, at volume fractions above 10% the effect of fly ash on concrete setting time starts to become more pronounced [66].

Brooks [50] study came up with a model able to predict the initial setting time of concrete with fly ash and without fly ash. The study concluded that the initial setting time is given by initial spacing of unhydrated cement particles divided by a rate coefficient. This is applicable for cement with partial replacement of about 60% fly ash. The final setting time related to the initial setting time by a factor of 1.35 with an average error of 13% [67]. However, this study failed to take into account that the variations between fly ash from different geographical locations and the different classes of fly ash.

Research carried out by Naik [48] concluded that generally the addition of fly ash up to about 60% caused significant delay in both the initial and final setting time of concrete. Beyond 60% fly ash volume fraction the trend reversed with both the initial and final setting time reducing. Figure 3 shows the general trend of setting time with increase in fly ash content [66]. At 70% and higher fly ash volume fraction the setting of concrete occurs at a faster rate. This necessities the addition of a retarding admixture to allow enough time for good workability of the concrete paste. The increase in setting time is unfavourable as the concrete will set before it is moulded into the desired slab.

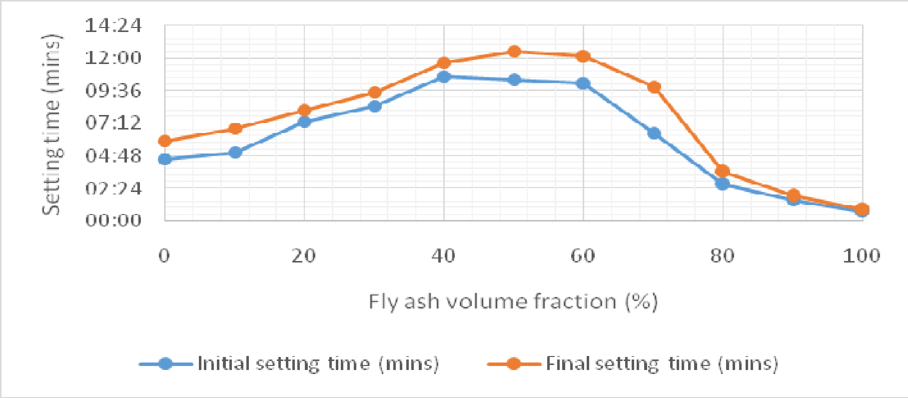

Figure 3: Setting Time of Concrete Mixture Containing Fly Ash [68].

4.5 Heat of Hydration

The heat of hydration of concrete is defined as the heat generated as a result of an exothermic reaction between cement and water [69]. Kim [70] stated that when the minerals compounds which include alite (C_3S), belite (C_2S), aluminate (C_3A) and alumina ferrite (C_4AF) contained in cement are mixed with water, hydration products will be produced. These include calcium silicates composed of (C_3S) and (C_2S). These two calcium silicates produce hydration reactions. Equations 3 and 4 give the hydration reaction of the calcium silicates.

$$2C_3S + 11H \rightarrow C_3S_2H_8(C - S - H) + 3CH\ (calcium\ hydroxide) \tag{3}$$

$$2C_2S + 9H \rightarrow C_3S_2H_8(C - S - H) + CH(calcium\ hydroxide) \tag{4}$$

The C-S-H gel gives a representation of the binder of cement paste and has an influence on the strength and durability of concrete. The heat of hydration of concrete can be broken down into five stages as shown in figure 4.

In stage one shown in figure 4, an ettringite is formed from aluminate reacting with water. This reaction is exothermic and is the first peak in the hydration temperature graph. Stage two is commonly referred to as the dormancy stage and occurs for about 2–4 hours after the initial mixing of cement and water. Small amount of heat is generated during this stage. In stage three, which is known as the acceleration stage calcium silicate hydrate and crystalling calcium hydroxide form in an exothermic reaction. This stage has a second peak of heat of hydration. In stage four, which is the deceleration stage the reaction between calcium silicate hydrate and crystalline calcium hydroxide with water and undissolved cement slows down the reaction. This gives a decline in the heat of hydration. Lastly, in stage five, belite dissolves releasing calcium ions slowly, this is a slow reaction with small amount of heat released.

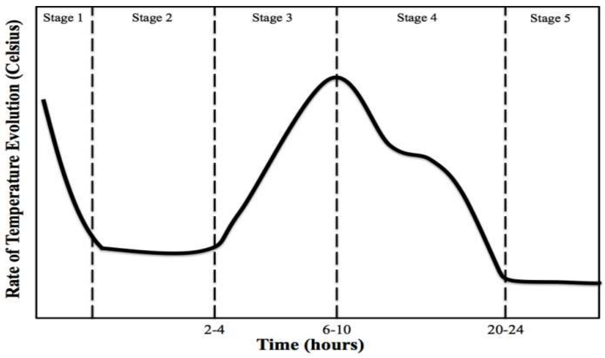

Figure 4: Stages of Heat Generated in the Hydration Process of Concrete [37, 71].

The hydration process in concrete containing fly ash is complicated due to two inter related time dependent processes which are the cement hydration and pozzolanic reaction of fly ash [72]. Moghaddam et al [54] study reported that there was a cumulative decrease in heat evolution with the increase in fly ash volume fraction in concrete. However, the finer the fly ash particles the greater the heat it produced in comparison to the coarser grade fly ash particles [73]. The heat of hydration of high volume concrete was reported to reduce with the addition of fly ash [74, 75, 76]. Feng et al [57] research measured the heat of hydration of the concrete sample using Toni Technik 7338 Isothermal Differential Calorimeter. The hydration heat was measured within 72 hours. Further study by Feng et al [57] concluded that ground fly ash lowers the hydration heat when compared to pure cement. The use of fly ash in increasing volume fractions increases the outer surface area available for fly ash, hence, the amount of calcium ions absorbed increases [77]. This inhibits the build-up of calcium ions during the early hydration stages prolonging the setting time. Thus, the heat of hydration decreases [78]. However, most of the research failed to account for reactions that would occur with different classes of fly ash bearing in mind the difference in particle size of fly ash as well. It is worth noting that high heat of hydration can cause cracking and deterioration of concrete mechanical properties. Hence, concrete that contains very high volume fraction of very fine fly ash and generates more heat might become more likely to develop surface cracks.

4.6 Permeability

Permeability of concrete is defined as the ease with which a fluid can pass through the concrete under a pressure difference and is measured in term of co-efficient of permeability [79]. When the flow is steady the co-efficient of permeability is determined by Darcy’s law.

Water permeability of concrete slabs is an important parameter to the serviceability and durability of concrete when it is subjected to harsh environments. Since, water is a major agent in the deterioration of cured concrete [80]. Concrete slabs reinforced with steel tend to lose strength on corrosion of steel reinforcement due to water exposure. Study by Supit et al [76] concluded that inclusion of fly ash in the concrete mixture reduces the volume of permeable void by as much as 6–11% in comparison to unreinforced concrete. However, study by Chindaprasirt et al [58] concluded that addition of fly ash increased the porosity of concrete with increase in volume fraction of fly ash [81, 82]. This contradiction can be explained by looking at the type of fly ash used and its source. The chemical and physical properties of fly ash tend to vary with its geographical location. A lot of research has focused on the ways of improving the permeability and durability of concrete. For most types of fly ash the addition of admixtures such as pozzzolanic materials reduces the porosity of concrete leading to increased impermeability of concrete [83]. The pozzolanic reaction of fly ash improves the microstructure of concrete in comparison to using just Portland cement. Concrete containing fly ash can be 5–20 times less permeable than pure concrete with just cement. Reduced permeability assists in increasing the life span of steel reinforced concrete. As water will not be as likely to seep in and speed up the corrosion of steel reinforcements.

5. MECHANICAL PROPERTIES OF CONCRETE SLABS CONTAINING FLY ASH

Partial replacement of cement with fly ash in concrete slabs has a positive effect on the compressive and flexural strength of concrete. Concrete is mainly subjected to compressive stress during its use as a load bearing structure. However, flexural forces are also acting on the concrete slab. Flexural strength measures the ability of the concrete to withstand failure under bending stress. The effect of fly ash on the concrete slab strength properties was reviewed in this study under the following subheadings.

5.1 Compressive Strength

Compressional strength in concrete structures is one of the most important strength parameters. This is mainly due to the fact that during the working life of concrete slabs the main forces exerted are compressional forces. Fly ash as a partial replacement of cement on one hand, tends to have a negative effect on the compressive strength for the first 28 days. On the other hand, fly ash has a positive effect on the long term ultimate compressive strength of the concrete due to the pozzolanic nature of fly ash [55]. Research carried out by Barbuta et al [62] reported that the highest compressive strength of fibre and fly ash reinforced concrete slab is obtained at 10% fly ash volume fraction after 28 days [84].

Rohman et al [63] studied the effect of fly ash concentration on the compressive strength of concrete and concluded that the compressive strength of concrete improved at 16.4% volume fraction of fly ash and then decreased significantly up to 20% [85, 86]. An increase in the quantity of fly ash volume fraction decreases the compressional strength of concrete. This implies that the addition of fly ash must be limited to below 20% to get the best short term compressional strength.

Class F fly ash has low lime quantity. This result in the reduction of compression strength of concrete made from this type of fly ash with increase in its fly ash mass fraction. However, the ultimate compressive strength of the concrete increases in time as the concrete cures due to pozzolanic activity of the fly ash [87, 88]. The compressive strength increment for concrete slabs containing fly ash continues over a longer period of time spanning months in comparison to the concrete unreinforced with fly ash [89]. The hydration of fly ash within concrete occurs slowly and significant strength realised after 28 days and this explains the low compressive strength during the initial stages of curing. After fabrication of concrete slabs containing fly ash the concrete microstructure has a copious amount of un-hydrated fly ash. However, after curing of approximately a year the fly ash is more compact and has no sign of un-hydrated fly ash [90]. Concrete that shows the highest compressive strength is the one containing fly ash with the highest degree of fineness of between 1.9 and 17.2 micron [91]. The use of 5, 10 and 15% of fine fly ash volume fraction gives ultimate compression strength ranging between 3 and 16% higher than concrete without fly ash content [92]. Ramaswamy et al [69] reported that the replacement of 40% volume fraction of fly ash gives the optimum long term compressive strength [58]. Research carried out by Celik et al [71] concluded that the fly ash particle size had the most dominant effect on the compressive strength over the chemical composition [93]. However, not much conclusive research has been done on the effect of fly ash particle size on the ultimate compressive strength. Study by Reddy [72] reported that the best compressive strength in the 7 and 28 day range is obtained at about 20% fly ash volume fraction [94].

5.2 Flexural Strength

According to research carried out by Barbuta et al [61], the maximum flexural strength for the cement composite containing glass fibre and fly ash was obtained at fly ash volume fraction of 40%. For fly ash concrete composite with polyester fibres as reinforcement the maximum flexural strength was observed at 20% volume fraction fly ash [95]. Feng et al [57] conducted a research on the addition of fly ash at 25% volume fraction and ground fly ash at the same volume fraction. Tests were carried out on the flexural strength over time. The study concluded that the fineness of the fly ash particles had an effect on the ultimate flexural strength of the concrete. This is due to the fact that fine fly ash particles fill the pores between the hydration products and this increases the density of the microstructure and hence giving improved flexural strength. The maximum obtainable flexural strength has been observed at 50% addition of fly ash content for all ages of the concrete[5]. Research by Solanki [74] concluded that the highest flexural strength of concrete with fly ash is obtained at 20% as shown in Figure 5[96].

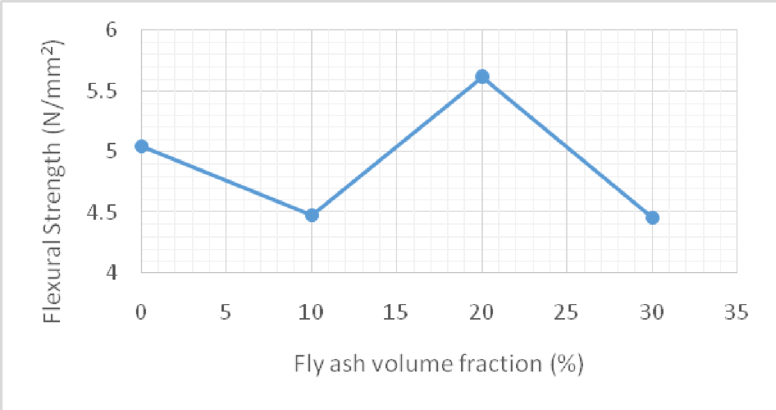

Figure 5: Effect of Fly Ash Volume Fraction on Flexural Strength of Concrete Slabs [97, 96].

6. SUMMARY AND DISCUSSIONS

Fly ash is obtained from thermal power stations as a by-product of the coal combustion process. Fly ash is sometimes considered as a waste material and potential source of pollutant if not disposed of appropriately. Fly ash has a potential use in highway construction, agriculture, construction of embankments and concrete. However, not much research has been carried out on the leaching of heavy metals from the fly ash into the soil and ground water contamination. Due to its pozzolanic nature fly ash is a suitable material to be used as a partial replacement of cement in the concrete manufacturing. The pozzolanic reaction occurs when fly ash is added to the cement in the presence of water. The active chemical components of fly ash which include silica and alumina react with calcium hydroxide [98, 99, 100, 101]. The partial replacement of cement with fly ash has a number of advantages to both the workability and mechanical properties of the resultant concrete.

Substitution of cement with fly ash in concrete slab mixture increases the workability of the concrete making it easier to pump and place. This increase in workability can be attributed to the spherical shape of the fly ash particles which allow the concrete paste to flow easily by reducing the friction at the aggregate paste interface. The fly ash particles act like miniature ball bearing in within the concrete mixture. The higher the volume fraction of fly ash the higher the workability of concrete paste [54]. However, the flow of the concrete paste must still be maintained as viscous to allow ease of moulding. There has not been enough research to explore the effects of high fly ash volume fraction on the viscosity of the concrete paste.

Use of fly ash in concrete paste increases the cementitious compounds, minimizing the amount of water required in the mixture and reducing the bleed channels. These properties give concrete with low permeability and reduced quantity of internal voids. Reduction in internal voids has a positive influence on the strength of the concrete. Fly ash increases the bleed water of concrete significantly for the first 90 minutes. Increase in bleed water has an advantage of preventing premature cracking of concrete on the surface due to drying out. However, the higher bleeding tends to create water voids within the concrete reducing the bond between the aggregate and the cement paste. The settling time of concrete is increased with increase in fly ash volume fraction. Increase in setting time allows ease of transportation and moulding of the concrete paste. However, it delays the construction of concrete slabs.

The slump of concrete is reduced with an increase in fly ash volume fraction. This can be attributed to the decrease in the water quantity in concrete containing fly ash. The higher the replacement level of cement with fly ash the

lower the quantity of water required in the mixture. This has a direct positive influence on the slump value of the concrete. Furthermore, the lower water requirement of concrete containing fly ash has advantage in construction logistics of concrete slabs and cost.

The strength difference between concrete containing fly ash and that without becoming pronounced after 28 days. Generally, concrete containing fly ash has a slower rate of strength development and results in higher values at a later age strength that is more than 28 days. Increasing the volume fraction of fly ash, however, has some disadvantages such as extended setting time of concrete and slow strength development. The compressive strength of concrete is reduced with the addition of fly ash. However, the long term compressive strength is increased after the fly ash has reacted fully. The flexural strength of concrete containing fly ash is higher than unreinforced concrete. Use of fly ash increases the aged strength of concrete that is greater than 28 days significantly. This can be attributed to the fly ash particles filling the pores between the hydration products. Thereby, increasing the density of the microstructure which results in increased flexural strength. The flexural strength of concrete containing fly ash has been shown to give best results at 20% fly ash volume fraction. For volume fractions exceeding 20% the flexural strength of the concrete slabs decreases considerably [95, 96, 77]. However, not much research is available on the effect of different classes of fly ash in the concrete slab strength properties.

7. CONCLUSIONS

Fly ash can be used successfully as a partial cement replacement for concrete slabs. As a result of the use of fly ash a number of benefits are realised in terms of workability and strength properties. The workability of concrete mixture is improved with the addition of fly ash. Furthermore, the strength properties are seen to improve. The compressional strength increases up to 20% fly ash volume fraction. The compressional strength increases as well in a similar trend. It is worth noting that the short term compressional strength of concrete slabs containing fly ash is not very good due to the pozzolanic reactions which will still be taking place. However, the long term compressional strength of more than 28 days is significantly improved. Further, research is necessary to study the effect of fly ash particle size on workability and strength properties of concrete. There is also a gap in knowledge on the effect of different classes of fly ash on the workability properties as well as compressive and flexural strength at various replacement levels of concrete.

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